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Gemini-South + FLAMINGOS Demonstration Science: Near-IR Spectroscopy of the $z = 5.77$ Quasar SDSS J083643.85+005453.3[1]

Daniel Stern[2], Patrick B. Hall[3,4], L. Felipe Barrientos[3], Andrew J. Bunker[5], Richard Elston[6], M. J. Ledlow[7], S. Nicholas Raines[6], & Jon Willis[8]

ABSTRACT

We report an infrared 1−1.8 μm (J + H-band), low-resolution (R = 450) spectrogram of the highest-redshift radio-loud quasar currently known, SDSS J083643.85+005453.3, obtained during the spectroscopic commissioning run of the FLAMINGOS multi-object, near-infrared spectrograph at the 8m Gemini-South Observatory. These data show broad emission from both C IV λ1549 and C III] λ1909, with strengths comparable to lower-redshift quasar composite spectra. The implication is that there is substantial enrichment of the quasar environment, even at times less than a billion years after the Big Bang. The redshift derived from these features is $z = 5.774 \pm 0.003$, more accurate and slightly lower than the $z = 5.82$ reported in the discovery paper based on the partially-absorbed Lyα emission line. The infrared continuum is significantly

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[2]Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 169-506, Pasadena, CA 91109

[3]Pontificia Universidad Católica de Chile, Departamento de Astronomía, Facultad de Física, Casilla 306, Santiago 22, Chile

[4]Princeton University Observatory, Princeton, NJ 08544-1001

[5]Institute of Astronomy, Cambridge, UK

[6]Astronomy Department, University of Florida, Gainesville, FL

[7]Gemini-South Observatory, La Serena, Chile

[8]European Southern Observatory, Alonso de Cordoba 3107, Casilla 19001, Santiago 19, Chile

redder than lower-redshift quasar composites. Fitting the spectrum from 1.0 μm to 1.7 μm with a power law $f_\nu \propto \nu^{-\alpha}$, the derived power law index is $\alpha = 1.55$ compared to the average continuum spectral index $\langle\alpha\rangle = 0.44$ derived from the first SDSS composite quasar. Assuming an SMC-like extinction curve, we infer a color excess of $E(B-V) = 0.09 \pm 0.01$ at the quasar redshift. Only $\approx 6\%$ of quasars in the optically-selected Sloan Digital Sky Survey show comparable levels of dust reddening.

Subject headings: galaxies: galaxies: active — quasars: general — quasars: individual (SDSS J083643.85+005453.3)

1. Introduction

Quasars are amongst the most luminous objects known in the Universe, visible at immense lookback times corresponding to when the universe was less than a tenth its current age. They provide ideal probes of the conditions of the early universe, showing, for instance, that the universe was optically thick to Lyα at $z \gtrsim 6$, likely evidence of a neutral universe seen prior to *an* epoch of reionization (Becker et al. 2001; Djorgovski et al. 2001; Kogut et al. 2003). For the most distant quasars, however, cosmological redshifting and the effects of foreground hydrogen absorption make these sources largely invisible at optical wavelengths: the most distant quasar known currently, SDSS J114815.64+525150.3 at $z = 6.43$, shows essentially no emission blueward of 9000 Å (Fan et al. 2003). Furthermore, for these most distant systems, optical observations are largely restricted to the rest-frame ultraviolet light around Lyα. Lyα is a notoriously fickle line, vulnerable to absorption from small amounts of gas and dust; redshifts derived from Lyα alone are systematically overestimated, though no better feature is typically available from the discovery optical spectra.

Near-IR observations of the highest-redshift quasars provide the opportunity to observe complete rest-frame ultraviolet spectra of these systems, probing out to Mg II λ2800 for the most distant quasars. Such observations are essential for deriving accurate redshifts, which, in turn, are necessary for molecular line searches (e.g., Bertoldi et al. 2003) and studies of the proximity effect. For instance, Iwata et al. (2001), based on *ten* days of observations with the Nobeyama Millimeter Array, report a non-detection of CO ($J = 6-5$) emission in the quasar SDSS J104433.04−012502.2, assuming the redshift of $z = 5.80 \pm 0.02$ derived from the optical spectrum (Fan et al. 2000). Near-IR observations of C IV λ1549 with the Keck telescope revised the redshift of this quasar to $z = 5.74$ (Goodrich et al. 2001), implying that the Iwata et al. (2001) observations missed the frequency range in which CO ($J = 6-5$) emission would be expected. Near-IR spectroscopy of the highest-redshift quasars also allows

estimates of the central black hole mass in these systems (e.g., Vestergaard 2002; Barth et al. 2003; Willott, McLure, & Jarvis 2003). Creating black holes with masses $\gtrsim 10^9 M_\odot$ within a Gyr of the Big Bang remains an outstanding astrophysical challenge (e.g., Kauffmann & Haehnelt 2000; Wyithe & Loeb 2002).

On UT 2002 November 5–6 and 8–11, we used FLAMINGOS (Elston 1998; Elston et al. 2002) on the Gemini-South 8m telescope at Cerro Pachon to demonstrate the infrared spectroscopic capabilities of this unique instrument. FLAMINGOS — the **FL**orid**A** **M**ulti-object **I**maging **N**ear-infrared **G**rism **O**bservational **S**pectrometer — is a combination wide-field near-IR imager and multi-object spectrometer (MOS) built by the University of Florida. Central to the design of FLAMINGOS is a liquid nitrogen-cooled MOS wheel, holding up to 11 MOS plates, which can be thermally cycled in less than six hours. FLAMINGOS is the world's first fully-cryogenic, near-IR MOS spectrometer; it was designed to be a peripatetic visitor instrument, traveling between observatories such as Kitt Peak National Observatory, the Multiple Mirror Telescope, and the southern Gemini Observatory. At Gemini the 2048 $\times$ 2048 science-grade Hawaii-II HgCdTe array has a plate scale of $0\farcs078$ pix^{-1}, providing a $2.5' \times 2.5'$ field of view. In MOS mode it achieves spectral resolving powers of $R \sim 450$ for $0\farcs47$ wide slits, covering $J + H$ bands or $H + K$ bands simultaneously.

During this Demonstration Science run, an emphasis was placed on the MOS mode of FLAMINGOS, though we also observed several brighter single-slit sources to exercise the instrument. In this *Letter*, we report on observations of the high-redshift quasar SDSS J083643.85+005453.3 (hereafter SDSS J0836+0054; Fan et al. 2001). At the time of our observations, SDSS J0836+0054, reported to be at $z = 5.82$, was the third highest redshift quasar in the refereed literature. With a 1.11 ± 0.15 mJy unresolved counterpart in the 20cm FIRST radio survey (Becker, White, & Helfand 1995) and a Galactic absorption-corrected $0.5 - 2.0$ keV flux of $F_{0.5-2.0} = 1.03 \times 10^{-14}$ ergs cm^{-2} s^{-1} (Brandt et al. 2002), SDSS J0836+0054 is also amongst the most distant X-ray sources known currently and remains the most distant radio source in the literature. Additional results from this Demonstration Science observing run will be reported by Hall et al. (in preparation).

2. Observations and Data Reductions

We observed SDSS J0836+0054 on UT 2002 November 9 using FLAMINGOS on the Gemini-South 8m telescope. The night was photometric and reported $0\farcs8$ seeing. We used a $0\farcs468$ wide slit, the JH grism, and the JH filter, providing low-resolution ($R = 450$) spectroscopy over the wavelength range of $1.0 - 1.8$ μm. The quasar was initially centered in the slit using JH imaging. At the time of our observing run, Fowler sampling was not

functional for the FLAMINGOS instrument, leading to excessive readnoise. For imaging, where the bright near-IR sky provides background-limited data with short exposure times, this was not a problem. However, for spectroscopy, the effect was deleterious in the J and H bands. In order to achieve background-limited data, we observed SDSS J0836+0054 for three dithered 1500 s integrations, unusually long exposure times for near-IR observations. The total integration time was 4500 s and the observations were obtained at moderate (~ 1.45) airmass.

Data reductions were done with a modified version of the `BOGUS` slitmask reduction software[9] within the `IRAF` environment, and followed standard near-IR slit spectroscopy procedures. After multiplying by the gain of 4.1 e^{-} DN^{-1} and subtracting dark frames from the science and calibration data, the science frames were flattened using a median-filtered, normalized quartz lamp spectrum taken immediately subsequent to our science observations. Cosmic rays were then identified and masked out. We did a first-pass, pairwise sky subtraction by subtracting the average of the alternate, dithered science frames from each individual science frame. As the near-IR sky varied substantially over the 4500 s time frame that our data was taken in, a second-pass sky subtraction was necessary, using a low-order fit along the spatial axis. The two-dimensional data, which provided good background subtraction and background-limited data, were then combined and the spectrum of SDSS J0836+0054 was extracted. We wavelength calibrated the data using observations of Ar lamps obtained thru the slit immediately subsequent to the science frames, and adjusted the wavelength zeropoint based on telluric emission lines.

We flux calibrated the SDSS J0836+0054 spectrum using spectra of the bright AOV Hipparcos stars 113982, 112179, and 28112 obtained at low (~ 1.1) airmass. The first of these stars was observed on the same (photometric) night as SDSS J0836+0054. The latter two stars were observed on UT 2002 November 10, a photometric night which suffered from high winds and associated variable and poor seeing. The resultant slit losses were substantial and variable; we therefore normalized these data to the UT 2002 November 9 spectrum of Hipparcos 113982, using them to define the shape, but not the amplitude, of the sensitivity curve. We interpolated across the Paschen absorption features in the A0V spectra in order to create the final sensitivity curve, which was then used to calibrate the spectrum of SDSS J0836+0054, shown in Fig. 1. We note that due to observational limitations, all spectra were obtained at a position angle of zero degrees, not the parallactic angle. For optical spectroscopy, atmospheric differential refraction will cause such a strategy to yield erroneous measurements of spectral energy distributions, particularly for narrow slits. In

[9]`BOGUS-IR` is available at `http://zwolfkinder.jpl.nasa.gov/~stern/bogus.html`.

the near-infrared, however, this is not nearly as severe a problem. Following Filippenko (1982), we find that atmospheric differential refraction will compromise our observations of the broad-band, near-infrared color of SDSS J0836+0054 at only the 2−3% level across the $1.0 - 1.8\mu$m wavelength region.

3. Results

3.1. C III] λ1909 emission

Our near-IR spectrogram provides a more accurate redshift determination for SDSS J0836+0054 than was possible from the discovery optical spectrum, which, based on heavily-absorbed Lyα emission and Lyβ/O VI λ1035 emission, provided a redshift of $z = 5.82$ (Fan et al. 2001). The C III] λ1909 line is particularly useful for this endeavor as it is a strong line close to the systemic redshift. Vanden Berk et al. (2001) note that, unlike Lyα and C IV λ1549, C III] λ1909 shows little object-to-object variation amongst over 2200 Sloan digital sky survey (SDSS) quasar spectra they analyze. As a counterexample, C IV λ1549 occasionally shows blueshifts of several thousand $\mathrm{km\,s^{-1}}$ (Richards et al. 2002). Fitting the C III] λ1909 line with a Gaussian profile and correcting for the typical C III] λ1909 velocity blueshift of 224 $\mathrm{km\,s^{-1}}$ relative to [O III] λ5007 (Vanden Berk et al. 2001), we calculate a redshift of $z = 5.77$ for SDSS J0836+0054. We also cross-correlated our infrared spectrum with the SDSS composite quasar spectrum, finding a redshift of $z = 5.774 \pm 0.003$ for SDSS J0836+0054. As discussed in §1, accurate redshifts are essential for molecular line searches and studies of the proximity effect. The revised redshift implies that a substantial fraction of the Lyα emission line is absorbed.

Our near-IR spectrum shows a strong detection of the C III] λ1909 line at 1.2910 μm, with a strength of 3.0×10^{-15} $\mathrm{ergs\,cm^{-2}\,s^{-1}}$. Vanden Berk et al. (2001) present a composite quasar spectrum derived from over 2200 Sloan digital sky survey spectra. In this composite, C III] λ1909, which is slightly blended with Si III] λ1892 and several Fe III transitions, has an equivalent width of 21.2 Å, and has a velocity width of 3700 $\mathrm{km\,s^{-1}}$ (FWHM). SDSS J0836+0054, with a C III] λ1909 rest-frame equivalent width of 19 Å and a velocity width of 6300 $\mathrm{km\,s^{-1}}$, has comparable values. Also, SDSS J0836+0054 clearly has substantial N V λ1240 emission (Fan et al. 2001). These results, though not unique for high-redshift quasars (e.g., Goodrich et al. 2001), are quite remarkable: the emission-line gas of quasars seen when the universe was less than a Gyr old has a similar metallicity to low-redshift quasars. This gas, calculated to have solar or higher metallicity (e.g., Hamann & Ferland 1999; Dietrich et al. 2003), requires substantial *and* rapid enrichment.

Assuming that the broad-line region (BLR) gas dynamics is dominated by gravitational forces, combining the radius of the BLR ($R_{\rm BLR}$) derived from reverberation mapping studies with the velocity of the emission line gas derived from the spectrum ($v_{\rm BLR}$), one can derive a virial estimate of the central black hole mass, $M_\bullet = G^{-1}\ R_{\rm BLR}\ v^2_{\rm BLR}$. Reverberation studies find a correlation between $R_{\rm BLR}$ and continuum luminosity (Kaspi et al. 2000), so that black-hole mass estimates are possible from single-epoch spectroscopic data. However, since reverberation mapping studies have traditionally targeted lower-redshift, brighter sources, this relation was initially calibrated for Hβ which is inaccessible at high redshift. Recently, McLure & Jarvis (2002) and Vestergaard (2002) have calibrated the relationship for Mg II λ2800 and C IV λ1549, respectively, allowing black-hole mass estimates at higher redshifts. No C III] λ1909 calibration is currently available, unfortunately, while our C IV λ1549 detection is of insufficient signal-to-noise to make a meaningful black-hole mass measurement. We note that Mg II λ2800 resides at 1.90 μm at the redshift of SDSS J0836+0054, an inaccessible wavelength for ground-based observations, residing between the H and K bands.

3.2. Red continuum

The most striking aspect of the near-IR spectrum of SDSS J0836+0054 is its red color. Fitting the spectrum over $\lambda\lambda\ 1.0 - 1.7\ \mu$m (rest-frame $\lambda\lambda_0\ 1480 - 2510$ Å) with a power law $f_\nu \propto \nu^{-\alpha}$, we derive a power law index of 1.55, significantly redder than the $\langle\alpha\rangle = 0.44 \pm 0.1$ continuum power-law index derived by Vanden Berk et al. (2001) for the SDSS composite quasar for rest-frame wavelengths $\lambda\lambda_0\ 1300 - 5000$ Å and redder than the $\langle\alpha\rangle = 0.57 \pm 0.33$ derived by Pentericci et al. (2003) for a sample of 45 high-redshift SDSS quasars imaged in the near-infrared. Some of this difference derives from Fe II emission at $\lambda\lambda_0\ 2200 - 2600$ Å mimicking a strong continuum. Indeed, Freudling, Corbin, & Korista (2003) have recently reported detection of Fe II emission in SDSS J0836+0054 based on very low-resolution ($R \sim 200$) *Hubble Space Telescope* near-IR spectroscopy. We note that their spectrum is also noticeably redder than the composite quasar spectrum it is plotted against, as well as shows C III] λ1909 blueshifted relative to the composite, plotted for $z = 5.82$. Our spectrum shows an upturn at 1.5 μm associated with Fe II. Fitting the Vanden Berk et al. (2001) composite over the rest-frame wavelength range available for SDSS J0836+0054, we find a spectral slope of 0.8 — significantly bluer than the spectral slope of SDSS J0836+0054. We infer that despite some contribution from Fe II emission, SDSS J0836+0054 clearly has an unusually red spectrum (Fig. 1).

What is the physical significance of a red spectral slope in a high-redshift quasar? Reddening is the obvious implication, requiring substantial dust in the quasar environment,

at an early cosmic epoch. The necessary processing of primordial hydrogen and helium has also been inferred from the strong C III] λ1909 emission feature. Comparing the spectrum of SDSS J0836+0054 with the SDSS composite spectrum reddened with an SMC-like dust-reddening law (Prevot et al. 1984), we estimate a color excess of $E(B-V) = 0.09 \pm 0.01$ at the quasar redshift. This implies an absorption of 1.36 ± 0.15 mag at 1550 Å. Richards et al. (2003) investigates the reddening of a sample of 4576 quasars from the SDSS, finding that only $\approx 6\%$ of quasars from the optically-selected SDSS show comparable levels of dust reddening.

Baker & Hunstead (1995) report on UV/optical spectral slope variations between various radio-loud quasar classes, placing the results in the context of orientation-driven unification schemes. They find that core-dominated, radio-loud quasars have bluer spectral slopes ($\alpha = 0.5$), albeit with very strong Fe II emission. Such quasars are thought to be viewed along the radio-jet axis. Lobe-dominated, radio-loud quasars have redder optical spectra ($\alpha = 1.0$) with weak Fe II emission, suggesting large column densities of dust obscure quasars viewed at larger inclinations to the radio-jet axis. Compact, steep-spectrum (CSS), radio-loud quasars, however, do not fit easily into this scheme: their compactness would suggest they are viewed along the radio-jet axis, but they have very red optical spectra ($\alpha = 1.4$) with no discernible 3000 Å Fe II bump, suggesting substantial extinction of the central nucleus. SDSS J0836+0054 is a radio-loud quasar with an unresolved morphology in the 20cm FIRST survey. Its optical spectral slope is similar to that for the CSS composite, though the weak Fe II detection suggests perhaps a lobe-dominated system. At present, neither multi-frequency nor higher-resolution radio data are available for SDSS J0836+0054.

4. Conclusions

We have presented a $J+H$, low-resolution spectrum of the high-redshift quasar SDSS J0836+0054, obtained during the Demonstration Science commissioning run of the FLAMINGOS multi-object, near-IR spectrograph at Gemini-S observatory. We detect broad C III] λ1909 emission, which we use to derive a more accurate redshift of $z = 5.774 \pm 0.003$ for this quasar. We also find a rest-frame ultraviolet spectral slope significantly redder than lower-redshift quasar composites, implying significant dust reddening of this system. Similarly, Bertoldi et al. (2003) have recently reported observations of dust in the host galaxy of a quasar at $z = 6.42$. For the *Wilkinson Microwave Anisotropy Probe* cosmology (Spergel et al. 2003), the universe is slightly less than 1 Gyr old at redshift $z = 5.77$. Our observations of SDSS J0836+0054 require substantial enrichment of the quasar environment, even at times only a billion years after the Big Bang.

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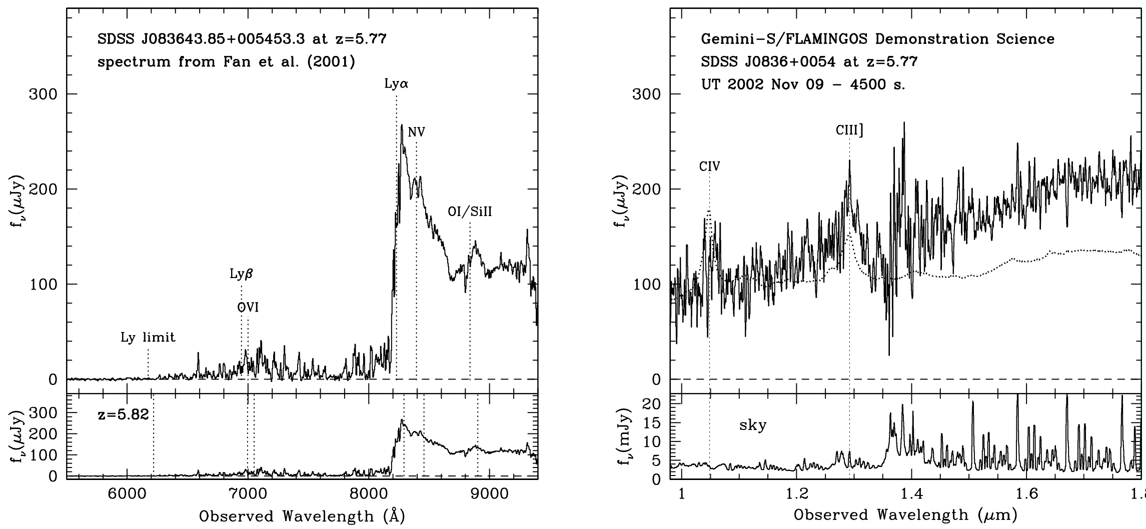

Fig. 1.— Optical and near-IR spectra of the $z = 5.77$ quasar SDSS J0836+0054. The discovery optical spectrogram, from Fan et al. (2001) and shown in the left panels, initially yielded a redshift of $z = 5.82$. This redshift, shown in the lower left panel, is based on the peak of the Lyα emission. The Gemini-S/FLAMINGOS near-IR spectrum has a good detection of the C III] λ1909 line, providing a more reliable redshift for the quasar. C IV λ1549 is poorly detected in our near-IR spectrogram: most likely, this is a result of poor S/N data, though the data also suggests C IV λ1549 self-absorption at the quasar redshift. The features at 1.35−1.4 μm in the near-IR spectrogram correspond to the region between the J and H bands, where atmospheric transmission is poor. The most striking aspect of the near-IR spectrum of SDSS J0836+0544 is its red color, discussed in §3.2. For comparison, the Vanden Berk et al. (2001) composite quasar is shown as a dotted line. Both spectra have been scaled to match the published imaging photometry for SDSS J0836+0054: $z^*_{\rm AB} = 18.74 \pm 0.05$ and $J_{\rm Vega} = 17.89 \pm 0.05$ (Fan et al. 2001).